Transportation Research Part D 35 (2015) 142–159

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

An aircraft performance model implementation for the estimation of global and regional commercial aviation fuel burn and emissions

D.K. Wasiuk [a], M.H. Lowenberg [a,*], D.E. Shallcross [b]

[a] Department of Aerospace Engineering, Queen's Building, University Walk, University of Bristol, Bristol BS8 1TR, UK
[b] Atmospheric Chemistry Research Group, School of Chemistry, Cantock's Close, University of Bristol, Bristol BS8 1TS, UK

ARTICLE INFO

Keywords:
Global aviation fuel burn
Global aviation emissions

ABSTRACT

Estimates of global aviation fuel burn and emissions are currently nearly 10 years out of date. Here, the development of the Aircraft Performance Model Implementation (APMI) software which is used to update global commercial aviation fuel burn and emissions estimates is described. The results from APMI are compared with published estimates obtained using the US Federal Aviation Administration's System for Assessing Aviation's Global Emissions (SAGE) for the year 2006. The number of global departures modelled with the APMI software is 8% lower compared with SAGE and reflects the difference between their commercial air traffic statistics data sources. The mission fuel burn, CO_2 and H_2O estimates from APMI are approximately 20% lower than those predicted by SAGE for 2006 while the estimate for the total global aircraft SO_x emissions is approximately 40% lower. The estimates for the emissions of CO, HC and NO_x are 10%, 140% and 30% higher than those predicted by SAGE respectively. The reasons for these differences are discussed in detail.

1. Introduction

The calculation of aircraft emissions is a crucial component in the study of their impact on the atmosphere and climate. The estimates of this impact are currently obtained using a combination of numerical models, in particular three-dimensional (3-D) Chemical Transport Models (CTMs) and 3-D or 4-D aircraft emissions inventories (Olsen et al., 2013). The 3-D or 4-D aircraft emissions inventories are customarily created using a combination of air traffic and aircraft performance data. This paper describes the development of software which can be used to build up a 4-D inventory of aircraft emissions (and more) and the development of a commercial air traffic statistics database which was used in support of this task. The software is a Linux server based application and will be referred to as APMI in the remainder of this article.

Aircraft emissions, NO_x in particular, first became of interest in the 1970s with the prospect of the introduction of a future supersonic fleet and its potential contribution to stratospheric ozone (O_3) depletion (Hidalgo and Crutzen, 1977). An inventory of aircraft NO_x emissions was first given by Bauer (1979) who based his work on that of Little (1975). 15 years later, starting in 1994, concerted efforts were made by a number of groups to construct detailed global 3-D inventories of aircraft emissions (IPCC, 1999). However, there has been little consistency and continuity in the estimates of global aviation fuel burn and emissions presented in the intervening 20 years. The inventories compiled during that time made use of different

* Corresponding author. Tel.: +44 1173315555.
E-mail address: m.lowenberg@bristol.ac.uk (M.H. Lowenberg).

http://dx.doi.org/10.1016/j.trd.2014.11.022
1361-9209/

sources of air traffic data sometimes scaling the number of departures to reflect the global air traffic volume as well as different sources of aircraft performance data and emissions calculation methods. The early inventories covered a handful of years in the 90s while the subsequent inventories gave estimates for up to 6 years, ending the timeline for the estimates at 2006.

In the early inventories and up until 2005, proprietary aircraft performance data were often used (Baughcum et al., 1994, 1996; Sutkus et al., 2001:), or a computationally and data hungry method (European Commission, 1997), or commercial software (European Commission, 1997; Gardner et al., 1997; Eyers et al., 2004) or in house methods (Schmitt and Brunner, 1997). In 2005 (Kim et al., 2005), the US Federal Aviation Administration (FAA) published a report describing SAGE, the System for assessing Aviation's Global Emissions in order to address these and other issues. SAGE was a high-fidelity computer model used to predict aircraft fuel burn and emissions for all commercial flights globally in a given year (Kim et al., 2005). The aim of SAGE was to provide the international community with a model based on non proprietary methods and data and a model that could be easily understood (no 'black boxes'). At the time of its publication SAGE was a US government research tool not intended for personal use, hence not itself publicly available. Subsequently, SAGE was incorporated into FAA's Aviation Environmental Design Tool (AEDT).

Because of global changes in air traffic patterns and geographically varying air traffic growth it has become necessary to update global and regional aviation fuel burn and emissions inventories for use in atmospheric models and policy studies (Wilkerson et al., 2010). Understanding the spatial and temporal distribution of aviation emissions, NO_x in particular, is important for modelling aviation's climate impacts (Wilkerson et al., 2010) because the emissions are not emitted uniformly over the Earth. Moreover, the atmospheric impact of aviation NO_x emissions is heterogeneous. The temporal and spatial variability of the aviation NO_x related atmospheric impacts has been established and quantified (Gilmore et al., 2013). Furthermore, the evaluation, comparison and improvement of the atmospheric models used in the assessment of the impact of aircraft emissions on the atmosphere would benefit from the existence of a range of current aircraft emissions estimates, as the ones available at present are nearly 10 years out of date.

The primary goal of this project was to model the impact of global aviation NO_x emissions on the global atmosphere and climate and, as we were unable to access suitable data to use with a 3-D CTM, we decided to implement an aircraft performance model with which to estimate current, global aviation NO_x emissions ourselves. Note that this has currently only been done by large organisations like NASA, FAA and the EC or with the support of these organisations. This paper describes this process, the end result of which is the APMI software. In developing the software we have followed the SAGE model documentation as closely as possible. We were limited in parts by data availability, for example, radar data, world fleet composition, data access and one instance of use of proprietary material (FAA's Emissions and Dispersing Modelling System (EDMS) used as the source of turboprop engine data in SAGE).

The remainder of this article is organised as follows: Section 2 gives a detailed account of the method. In Section 3 the results are given and compared to existing SAGE estimates for the year 2006, the year of overlap in results between the two models, which is followed by an in depth discussion of the reasons for the differences found. Finally, Section 4 gives the conclusions.

2. Method

The APMI software was constructed from three main components: a database of global commercial aircraft movements spanning the time period 2005–2011, a mathematical model of aircraft performance for all phases of a typical aircraft mission and a procedure for the calculation of aircraft emissions. All methods and tools that were used in the construction of the APMI software were free and publicly available (with the exception of the global aircraft movements database used) as well as established, validated by recognised aviation related organisations and previously used for similar purposes. Global air traffic movements data were sourced commercially as no free source of suitable information was identified. The APMI software was executed on the Scientific Linux OS, Release 5.7 (Boron) distribution on a University of Bristol Advanced Computing Research Centre (ACRC) server. It was written in the Perl Programming Language, Version 5.8.8 as its performance and ease of use fulfilled the requirements of this project. Also Perl was chosen due to the large number of file input/output processes that were identified as necessary. As a consequence, fast reading and processing from a text file was required and Perl is very well suited to this task. Next, each of the components and the freeware (free software) used is described in detail. The relationship between the individual components is shown in the form of a flow chart in Fig. 1.

2.1. Database of global commercial aircraft movements

In order to construct a detailed commercial (or any other) aviation mission fuel burn and emissions inventory, accurate records of air traffic movements are needed. There are many sources of such data, but based on an exhaustive search it is our understanding that no comprehensive, free and publicly available source of suitable data exists. Therefore, commercial sources were researched.

The leading commercial source of global flight schedules information (hence global air traffic movements) outside of the International Civil Aviation Organisation (ICAO) is the Official Airline Guide (OAG). OAG was the source of air traffic

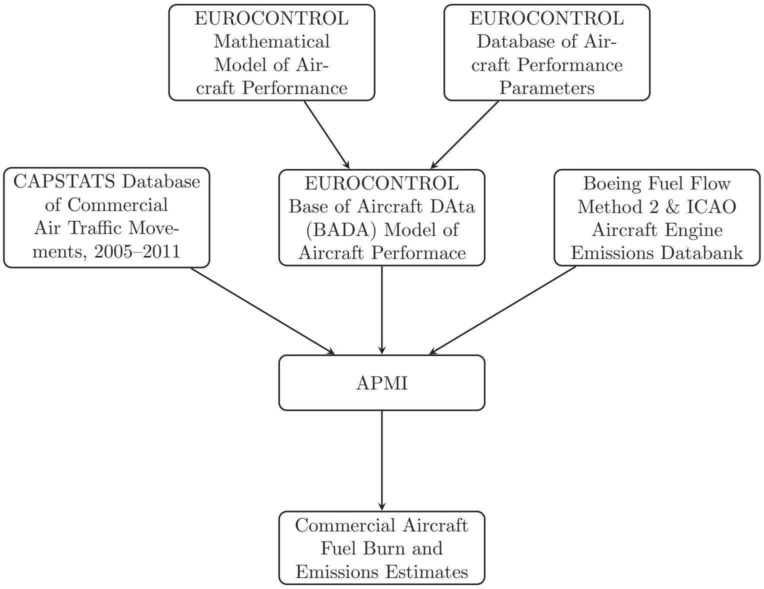

Fig. 1. A visual representation of the individual components of the APMI software.

movements statistics in the development of SAGE Version 1.5 (Kim et al., 2005). As obtaining funding for the high cost of the OAG database was not feasible, an alternative source, CAPSTATS, was identified at a much smaller cost. A one year CAPSTATS license was obtained at the end of 2010 and facilitated the use of global data between January 2005 and May 2012. The information purchased was: year, month, airline International Air Transport Association (IATA) code, airline name, equipment IATA code, equipment name, origin airport IATA code, origin airport name, origin country code, origin country name, origin continent code, origin continent name, destination airport IATA code, destination airport name, destination country code, destination country name, destination continent code, destination continent name, number of seats, number of departures, average capacity and available seat kilometres (ASKs). All information pertained to commercial, scheduled air traffic. Neither military nor non-scheduled traffic, such as business jets and charter flights, were included in the database. The data contained in CAPSTATS are similar to the data contained in OAG but are sourced separately (David Tellett, Flightglobal, personal communication, 2010). This means that two different companies collect the same data and sell it on or market it as two different products with or without add-ons, in this case OAG and CAPSTATS. It is the understanding of the provider (Flightglobal) that both databases have very similar, high quality coverage, but OAG's analytical tools (which were not required) are more feature rich than CAPSTATS (David Tellett, Flightglobal, personal communication, 2010).

The data were extracted from the web based database in the form of Microsoft Excel spreadsheets (default) and used to construct a fast and user friendly database. The scale and structure of the available data and the nature of the data queries required of it indicated that a relational database model would be most appropriate. The performance and ease of use of the free Relational Database Management System SQLite fulfilled the requirements of the project and was therefore chosen as the software with which to build the database.

In its original form (spreadsheets) CAPSTATS data contained over 6.5 million (6,694,449) rows of information (ca. 5.86 GB), was unstable and difficult to search. The spreadsheets were transferred to a Linux server and all the information was extracted. As the raw CAPSTATS data contained many redundancies, it was normalised. Redundancy is a situation where the information contained in a database may be repeated unnecessarily in several rows. Database normalisation is the process used in relational database modelling to organise data in order to minimise redundancy and to identify relationships contained within the data. The normalised database was significantly smaller (622 MB) and as a result, easier and faster to search and query. The smaller size of the normalised database also meant that it became easily portable.

Additional information was extracted from the database using the ASK data contained within it. An ASK is a measure of a flight's passenger carrying capacity (CAPA Centre for Aviation, 2014) and it is calculated as the number of seats on an aircraft multiplied by the distance travelled in kilometres. All unique routes were extracted from the database and given this relationship, the distance on each route was calculated by dividing the ASKs by the number of seats given. The normalised database was used to derive the input into the APMI software which is described in Section 2.5.

2.1.1. Validation of the global commercial aircraft movements database

The company Innovata collects the data contained in CAPSTATS in partnership with the International Air Transport Association. Around 900 (Innovata, 2012) airlines worldwide submit their flight schedules to Innovata on a voluntary basis (David Tellett, Flightglobal, personal communication, 2010). The airlines must themselves ensure the accuracy of their data. It is in their financial interest to do so, as the schedules are used by companies worldwide to advertise and sell the services of the airlines to customers all over the world. This is in line with how the data for the OAG database is collected as the OAG database is designed for the purpose of flight itinerary planning by airline passengers and travel agents (Baughcum et al., 1996).

An excerpt from OAG flight schedules corresponding to the month of September 2008 was obtained and CAPSTATS air traffic data for September 2008 was compared with this excerpt. First, it was checked if the two databases report data on the same routes, aircraft types and airlines. Ignoring all differences in the way the data were reported and structured and comparing the fields 'departure airport', 'departure country', 'destination airport', 'destination country', 'aircraft' and 'airline code', 94% of the data rows contained in OAG were also contained in CAPSTATS. An OAG row was said to be contained in CAPSTATS if the fields 'departure airport', 'departure country', 'destination airport', 'destination country', 'aircraft' and 'airline code' matched exactly in both databases. This means that there is a 94% overlap between the two databases in terms of the routes on which air traffic is reported and aircraft types and airlines that are being reported as servicing these routes.

Then, a check was performed of a portion of the 6% of the data rows where an exact match on the route, aircraft type and airline was not found in OAG and CAPSTATS. It was found that there was a partial match for those rows in CAPSTATS, with the only field not matching being the aircraft code. For example, the route Port Bouet Airport (Ivory Coast) to Mohammed V International Airport (Morocco) was reported in OAG to have been serviced with an aircraft with the IATA code 73G, while the CAPSTATS record of the IATA code for the aircraft is 738. The IATA aircraft code 73G pertains to a B737, Boeing 737-700, while the IATA aircraft code 738 pertains to a B738, Boeing 737-800. Using this example, the B738 has an overall slightly higher passenger and cargo capacity than the B737 and a slightly shorter maximum cruise range; both aircraft have the same fuel capacity and typical cruise speed and use engines from the same engine family with similar maximum thrust output and have almost identical basic dimensions (wing span, overall length, tail hight and interior cabin width) (The Boeing Company, 2014a,b). Hence they are very similar aircraft overall. Therefore it is concluded that CAPSTATS and OAG are in fact very similar in terms of route, aircraft type and airline coverage.

Having established that in 94% of the cases the two databases report data on same routes, it was checked if the two databases report equal number of departures on those routes. In 38% of the cases the number of departures matched between the two databases, in 56% of the cases the number of departures reported in CAPSTATS was higher, and in 6% of the cases the number of departures reported in CAPSTATS was lower.

Finally, the logical structure of the normalised database was checked by an independent database consultant with a satisfactory outcome. (Tom Gidden, http://www.linkedin.com/in/tomgidden).

Normalisation of the air traffic statistics data was not required as the CAPSTATS database contains detailed historical records of real world commercial flights as a monthly time line from January 2005 to December 2011 therefore scaling of the number of departures was not required.

2.2. BADA mathematical model of aircraft performance

The EUROCONTROL Experimental Centre (EEC) is the R&D branch of EUROCONTROL, the European Organisation for the Safety of Air Navigation, an intergovernmental organisation made up of 39 member states and the European Community. The EEC was the first organisation to perform a digital, real time simulation of the behaviour of an aircraft in a designated airspace. Subsequently, the EEC developed BADA (Base of Aircraft DAta), a mathematical model of aircraft performance and the associated databases of aircraft specific datasets. The mathematical model specification contains generic polynomial expressions used to calculate aircraft performance parameters, while an aircraft specific dataset (two ASCII files containing performance and operating procedures data) contains the specific values of the coefficients present in the mathematical model specification that particularise the BADA model for each aircraft type (EUROCONTROL, 2014).

The BADA mathematical model of aircraft performance is based on the total energy model (TEM) of an aircraft which can be considered to be a reduced point mass model. The TEM equates the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy (Suchkov et al., 2003), that is:

$$(T - D)V_{TAS} = mg\frac{dh}{dt} + mV_{TAS}\frac{dV_{TAS}}{dt} \tag{1}$$

where T (N) is the thrust (assumed to act parallel to the aircraft velocity vector), D (N) is the aerodynamic drag, m (kg) is the aircraft mass, h (m) is the altitude, g (9.80665 m/s^2) is the gravitational acceleration, V_{TAS} (m/s) is the true airspeed and $\frac{d}{dt}$

Table 1
International Standard Atmosphere (ISA), mean sea level conditions.

Variable	Value
Temperature	15 °C
Pressure	1013.25 hPa
Air density	1.225 kg/m^3
Speed of sound	340.294 m/s
Tropopause height	11,000 m

(s^{-1}) is the time derivative. The aircraft trajectory in the vertical plane can be altered using two independent control inputs, namely the throttle and the elevator. These are used to control any pair of variables out of the following three: thrust, speed and the rate of climb and descent. The combination speed and thrust is the most common, in which case assuming that velocity and thrust are independently controlled, Eq. (1) is used to calculate the resulting rate of climb and descent (Nuic, 2009).

The performance data file (OPF file) associated with the BADA mathematical model of aircraft performance defines the aircraft type (jet, turboprop, or piston), the aircraft mass (minimum, maximum, reference and maximum payload), the flight envelope (minimum speed, maximum speed, maximum altitude), the aerodynamics (lift, drag), the engine thrust and the fuel consumption (Suchkov et al., 2003). For the performance calculations, five configurations are specified and defined using threshold altitudes and speeds. These are take-off, climb, cruise, descent and landing. The corresponding threshold altitudes and speeds can be found in Nuic (2009).

Atmospheric variables required for the calculations that define each individual aircraft, for example lift and drag, are determined as a function of altitude and are based on the International Standard Atmosphere (ISA) which is summarised in Table 1. The entire flight path is modelled assuming ISA conditions due to a lack of real atmospheric conditions data, but the model supports calculations in non ISA conditions. Using values in Table 1, the temperature, pressure, air density and the speed of sound are calculated at and above sea level, below, at and above the tropopause. The equations used are listed in detail in Nuic (2009).

The operating procedures data file (APF file) associated with the BADA mathematical model of aircraft performance defines the speeds that are to be used in the climb (CL), cruise (CR) and the descent (DES) phases of the aircraft mission.

The BADA mathematical model of aircraft performance acknowledges that the way aircraft are operated varies with geographical location, airline and specific airspace procedures and policies and therefore the speed schedules defined in the APF file may differ from those used in reality.

2.3. Modelling of the aircraft mission

BADA Revision 3.7 User Manual (Nuic, 2009), BADA Revision 3.9 User Manual (Nuic, 2011) together with OPF and APF Revision 3.9 airframe specific files were used to simulate the behaviour of an aircraft in flight. The set of equations contained in the BADA Revision 3.7 User Manual and the BADA Revision 3.9 User Manual were used together with the airframe specific performance parameters contained within the OPF files and airframe and airline specific speeds and Mach numbers contained in the APF files. This allowed the calculation of the thrust, drag, fuel flow and fuel burn values at all stages of a prescribed aircraft mission.

An aircraft mission was divided into six stages: taxi out (TOUT), take-off (TO), climb (CL), cruise (CR), descent (DES) (including approach and landing) and taxi in (TIN). The TOUT and TIN phases were modelled entirely on the ground and were modelled separately, not using the TEM, as was the TO. For these stages, engine specific fuel flow values taken from the ICAO Aircraft Engine Emission Databank (ICAO, 2012) were used. These were combined with ICAO specified times in each phase (ICAO, 2011) for jet aircraft and with the Swedish Defense Research Agency's (FOI) (Hasselrot, 2002) times in each phase for turboprop aircraft. In the case of lack of airport specific information FOI's recommendation is to use ICAO specified times which was the case here. The details of the times in mode can be found in Table 2 for both jets and turboprops. The remaining stages (CL, CR and DES) were assigned fuel flow and fuel burn values for a given aircraft, mission type and distance using the BADA TEM. In all six stages the International Standard Atmosphere (ISA) was assumed, as nearly all the basic calculations of aircraft performance are performed under ISA conditions (Filippone, 2006).

2.3.1. Airframe and engine selection

Each supported aircraft type in the BADA database is identified by a four character designation code assigned by the ICAO (Suchkov et al., 2003). As aircraft types were entered in the CAPSTATS database using IATA codes, the IATA aircraft codes were translated into their corresponding ICAO codes using The Airline Codes Website (The Airline Codes Website, 2011). If the IATA code was not featured on The Airline Codes Website, the ICAO code was allocated using a manual search on the Internet using the IATA aircraft code and the aircraft name as entered in the CAPSTATS database as the search term. As a result, the 237 distinct IATA aircraft codes contained in CAPSTATS were mapped to 120 distinct ICAO codes. Next, each ICAO code was mapped to an OPF file from the BADA database using Nuic (2009). This mapping is a (mathematical) surjection, meaning that in some instances several ICAO codes are mapped to the same OPF file. In total, 80 distinct OPF files were used, 57 jets and 23 turboprops. Next, each ICAO aircraft code with the associated OPF file was mapped to an engine. The

Table 2
Times in mode.

Operating phase	Time in mode (min)	Thrust setting (% of rated thrust)
Taxi and ground idle, out	19	7
Take-off	0.7	100
Taxi and ground idle, in	7	7

engine name was usually contained in the OPF file mapped to the ICAO aircraft code. When this was not the case, an engine name was taken from EUROCONTROL (EUROCONTROL, 2013). The 80 OPF files were mapped to 78 unique engine types in total.

Piston powered aircraft were not included in APMI due to lack of engine data. Should the engine data become available in the future, conditional upon the existence of a BADA OPF file, piston aircraft can be included in APMI with ease.

This means that out of 237 equipment types contained in CAPSTATS, 215 (91%) were included in APMI. The 215 aircraft types included in APMI in turn account for 99.5% of the total global traffic recorded in CAPSTATS between 2005 and 2012.

Once each aircraft code in CAPSTATS had been assigned an ICAO code, an OPF file and an engine, the fuel burn and emissions calculations for the departures recorded in CAPSTATS went ahead.

2.3.2. Mission fuel burn algorithm

When modelling the flight trajectory of each departure, altitude increments of 10 ft were used between 0 and 100 ft, 100 ft between 100 and 1000 ft and 500 ft above 1000 ft. Maximum operating altitudes were specified in the BADA OPF files for all aircraft but in some instances behaved like an absolute ceiling and were unstable, meaning that the altitude could not always be reached while maintaining a sufficient rate of climb. Insufficient excess thrust was generated, as a result of which the rate of climb dropped to 0 m/s as the maximum operating altitude was approached. For this reason, the absolute ceiling could not be established in a reasonable time. It was also noted that very large distances were being covered near the maximum operating altitude, which agrees with the behaviour of an absolute ceiling. An alternative maximum operating altitude was defined where necessary as the operational ceiling at the altitude where the aircraft was able to maintain a minimum rate of climb of 2.5 m/s for jets and 0.5 m/s for turboprops (Greenwell, 2006).

In order to determine the total fuel load for each mission, each flight trajectory calculation was performed a fixed number, i, of iterations. In the first iteration, $i = 0$, the flight trajectory calculation was performed assuming that the start aircraft weight is equal to the aircraft maximum take-off weight (MTOW). A TOUT, TO, CL, CR, DES and a TIN was performed and the mission fuel burn, MFB_0, was calculated. The reserve fuel, RF_0, was calculated as described in SubSection 2.3.3. The total fuel load was defined as $FL_0 = MFB_0 + RF_0$. In the second iteration, $i = 1$, an average passenger weight including the luggage was assumed to be equal to 90 kg (ICAO, 2014b) and the start aircraft weight defined to be equal to the minimum aircraft weight + aircraft capacity $\times$ 90 kg + MFB_0. The minimum aircraft weight was defined for each aircraft in the OPF file to which it was mapped. The details of the individual aircraft capacities can be found in Wasiuk (2014). A TOUT, TO, CL, CR, DES and a TIN was performed and the mission fuel burn, MFB_1, was calculated, as was the reserve fuel, RF_1. The total fuel load was defined as $FL_1 = MFB_1 + RF_1$. The second step was repeated until $i = 6$, in which case $FL_i – FL_{i-1}$ was negligible in all cases. Note that when $i \leqslant 6$ and $FL_{i+1} = FL_i$ the algorithm stopped.

The average load factor for a single flight is the number of passengers divided by the number of seats, i.e., the ratio of all the occupied seats to all the seats available. The average load factor used in APMI is a four year average for the years for which global load factor data were available (2005–2008) (ICAO, 2014a) and where the years overlapped with those contained in the CAPSTATS database and it is equal to 75.5%.

2.3.3. Reserve fuel requirement calculation

Two separate reserve fuel calculations were performed depending on the mission type and two mission types were defined namely, domestic (d) and international (i). In both cases the reserve fuel was defined as the sum of a fixed reserve fuel quantity and a variable reserve fuel quantity. For a domestic mission, the fixed reserve fuel was set equal to the amount of fuel used cruising for 60 min (jet) or 45 min (turboprop) at the main mission cruise altitude at a fuel flow for the end of cruise aircraft weight. For an international mission, the fixed reserve fuel was set equal to the amount of fuel used cruising for 10% of the total trip airborne time at the main mission cruise altitude at a fuel flow for the end of cruise aircraft weight. The total trip airborne time is defined as the sum of the CL time, CR time and DES time.

The variable reserve fuel requirement for a domestic mission was defined as follows:

- Exercise a missed approach i.e., approach and abort landing at 3000 ft.
- Climb out to CR altitude following a missed approach.
- Let the jet reserve mission CR altitude = 20,000 ft if the main mission CR altitude $\geqslant$ 20,000 ft.
- Let the turboprop reserve mission CR altitude = 10,000 ft if the main mission CR altitude $\geqslant$ 10,000 ft.
- Let the jet reserve mission CR altitude = main mission CR altitude if the main mission CR altitude < 20,000 ft.
- Let the turboprop reserve mission CR altitude = main mission CR altitude if the main mission CR altitude < 10,000 ft.
- Fly to an alternate airport 200 nautical miles (jet) or 87 nautical miles (turboprop) away.
- Let the reserve mission distance = reserve CL distance + reserve CR distance + reserve DES distance.

The variable reserve fuel for an international mission was defined as for a domestic mission with the following element added:

- Hold at 1500 ft for 30 min.

Table 3
Jet cruise altitude bands, based on the probabilistic distribution of cruise altitudes from (Kim et al., 2005).

Jet mission distance (km)	Jet cruise altitude (ft)
Min range–200	$\geqslant 2,000, \leqslant$max CR alt
200–300	$\geqslant 7,500, \leqslant$max CR alt
300–400	$\geqslant 10,000, \leqslant$max CR alt
400–550	$\geqslant 20,000, \leqslant$max CR alt
550–900	$\geqslant 25,000, \leqslant$max CR alt
900+	$\geqslant 30,000, \leqslant$max CR alt

Table 4
Turboprop cruise altitude bands, based on the probabilistic distribution of cruise altitudes from (Kim et al., 2005).

Turboprop mission distance (km)	Turboprop cruise altitude (ft)
Min range–100	$\geqslant 2,000, \leqslant$max CR alt
100–200	$\geqslant 5,000, \leqslant$max CR alt
200–300	$\geqslant 7,500, \leqslant$max CR alt
300–400	$\geqslant 10,000, \leqslant$max CR alt
400–500	$\geqslant 15,000, \leqslant$max CR alt
500+	$\geqslant 19,000, \leqslant$max CR alt

2.3.4. Cruise altitude assignment

For every aircraft, mission and distance combination the cruise altitude was optimised for least fuel burn. The main mission cruise altitude was aircraft specific and a function of the mission distance. Given a mission distance, all possible cruise altitudes above a specified minimum and below and including the maximum cruise altitude (operational ceiling) were sampled and the altitude with the least fuel burn was selected. If at some step the distance covered in climb followed by an immediate descent was equal to the mission distance, the sampling of higher cruise altitudes was stopped. Depending on the engine type and the mission distance, the cruise altitudes were restricted as shown in Tables 3 and 4. The cruise altitude was restricted to these bands depending on the mission distance so as to allow the aircraft to spend some time in the cruise phase on shorter missions. As the tendency for the cruise altitude was to always be as high as possible, on shorter missions the mission profile would comprise a climb out followed by an immediate descent. The cruise altitude was restricted in order to counteract this.

The restriction of cruise altitudes to the bands shown in Tables 3 and 4 are based on Kim et al. (2005). Kim et al. (2005) developed the distribution of cruise altitudes from analysing large sets of Enhanced Traffic Management System radar data. The Enhanced Traffic Management System is the FAA's electronic recording of flight position and flight plan information used for air traffic management. It captures every flight within coverage of FAA radars, including scheduled, cargo, military, charter, and unscheduled flights. It also captures every flight that files a flight plan, whether or not the aircraft enters radar controlled airspace. The cruise altitude band restrictions are therefore based on analysed real world data, however, it must be noted that within these bands it was assumed that no Air Traffic Control conflicts arose which is not representative of reality. This is at present a necessary modelling assumption. The model would be greatly improved if instead of estimating the trajectory of each flight, a real world trajectory of each flight was reproduced in a numerical simulation. This is beyond data availability at present.

2.3.5. Cruise distance calculation

Given any mission distance $MISSION_d$, in the first iteration ($i = 0$), the cruise distance CR_d was set to 0 km. A climb out to the allocated cruise altitude was performed, followed by an immediate descent. The total distance was summed, $TOTAL_d = CL_d + CR_d + DES_d$. If $TOTAL_d < MISSION_d$, CR_d was reset to $CR_d + 1$ km. A climb out to the allocated cruise altitude was performed, followed by a cruise of CR_d km, followed by an immediate descent. The total distance was summed, $TOTAL_d = CL_d + CR_d + DES_d$. This was repeated until $TOTAL_d - MISSION_d < 1$ km.

2.3.6. Modelling assumptions and limitations

In this section, the assumptions made when designing APMI and the software's limitations are listed. They are:

- It was assumed that the CAPSTATS data were sufficiently accurate for the purpose of this study and that the scheduled departures recorded in CAPSTATS had taken place.
- Only jet and turboprop aircraft were modelled. Piston aircraft were not modelled due to lack of data.
- There were 237 distinct IATA aircraft codes contained in CAPSTATS. These were mapped to 120 distinct ICAO codes. Each ICAO code was mapped to an OPF file from the BADA database. This mapping is a (mathematical) surjection, meaning that

in some instances several ICAO codes are mapped to the same OPF file, hence generic aircraft codes were used. In total, 80 distinct OPF files were used, 57 jets, and 23 turboprops. Therefore, 80 generic aircraft types were used.
- The 80 generic aircraft types were mapped to 78 unique engine types in total.
- There were 237 distinct equipment types contained in CAPSTATS. There were 149 jets, 67 turboprops, 20 pistons, and 1 other. All jets and turboprops were mapped to a generic aircraft type and modelled.
- All trajectory simulations were performed in ISA conditions and assuming no winds (head or tail) due to data limitations. However, wind and temperature effects are not negligible. Baughcum et al. (1996) conducted a parametric study of wind and temperature effects on the calculated fuel use concluding that wind and temperature have a combined effect of 1.4–2.3% on round trip fuel burn (annual average) for East–West flights and about 1% for North–South flights, based on analyses for a Boeing 747-400. The effect is largest in the North Pacific. Since the airlines will try to fly routes which take advantage of the wind (rather than great circle routes), this may overestimate the effects of winds in the real world. Typically, an airline, given its choice of flight corridors, would try to maximise its tail wind and minimise the head wind on the return flight.
- The average passenger weight was assumed to be equal to 90 kg. This is the ICAO recommendation for passenger weight in the absence of data (ICAO, 2014b) and assumes that all passenger luggage is included in this weight.
- Cargo was not modelled. Each aircraft modelled in APMI has a specific maximum payload weight associated with it where the payload comprises passengers and cargo. It was assumed that all of the payload was made up of passengers.
- Freighters were not modelled in APMI as CAPSTATS does not record freighter movements. Only commercial passenger aircraft were modelled.
- A 75.5% load factor was used for all trajectory simulations. This load factor is a four year average for the years for which global load factor data was available (2005–2008) (ICAO, 2014a) and where the years overlapped with those contained in the CAPSTATS database. It should be noted that the load factor will have an important effect on the overall mission performance, including fuel burn and emissions and that in general, traffic efficiency of the global aviation fleet is affected by the load factor as Lee et al. (2010) point out. For example, Baughcum et al. (1996) carried out a parametric study evaluating the effect of payload and showed that increasing the payload from 70% to 75% can increase the fuel burn by 2.5% for a Boeing 737 flying between San Francisco and Los Angeles. Baughcum et al. (1996) concluded that the effect of varying the payload was small for long missions and large for short missions.
- Military and non scheduled air traffic was not accounted for. Military aviation fuel usage is considered to be a significant fraction of the total global aircraft fuel usage (Gardner et al., 1997) and it has been estimated that the military contribution to the emissions total is in the range of 10–13% (Wilkerson et al., 2010). Unscheduled flights have been estimated to account for as much as 9% of flights globally (Wilkerson et al., 2010).
- Fixed taxi out and taxi in times and fuel flows were modelled (7% engine power setting fuel flows and emission indices were assumed for the ground operations). This may have a significant effect on the total fuel burn, as for some missions the fuel used in these phases corresponds to a significant proportion of the total mission fuel burn.
- A mission was always performed in its entirety. Emergency landings and/or other contingencies where the mission was not performed in its entirety were not modelled.
- Delays, cancellations, or reroutings were not modelled.
- Domestic and international reserve fuel requirements were modelled differently.
- Different reserve mission cruise altitudes were used for jet and turboprop missions.
- A reserve mission was not performed. The reserve fuel was carried on board as contingency fuel and never used.
- The cruise altitude was restricted to altitude bands depending on aircraft type and mission distance. Within each band, the altitude with the lowest fuel burn was always selected.
- Each trajectory simulation followed a flight profile consisting of a continuous climb out to cruise altitude, followed by a cruise, followed by a continuous descent.
- Step climb was not performed. This will be important for intercontinental missions as the fuel carried on board on these missions accounts for a large portion of the total aircraft weight and the lighter the aircraft is, the higher it can cruise. Hence, on a long-haul intercontinental mission an aircraft will typically climb out to a certain cruise altitude, cruise at this altitude until a portion of the fuel has been burned and when lighter, request to climb to a higher altitude.
- A constant cruise altitude and speed were maintained during the entire CR phase of the trajectory simulation.
- Individual legs of missions with stopovers were modelled.
- Airport weight or runway restrictions were not modelled.
- All airports were assumed to be at sea level elevation.
- No account was taken of circuitous routing at take-off, approach and landing, hence, it was assumed that the runway always pointed in the direction of the destination when taking-off and that the runway was always aligned in the direction of the incoming flight when landing.
- Further operational anomalies were not captured in APMI, for example, a hold down which is a situation in which an aircraft is imposed with a climb restriction while it is still below 3,000 ft.
- Turns or air traffic control directions were not modelled.
- No air traffic control climb or cruise restrictions were modelled.

- The distances between each airport pair derived from CAPSTATS were assumed to be great circle distances as this is how aircraft fly in reality.

Naturally, these render the output from APMI only an approximation of actual flight conditions.

2.3.7. Validation

Apart from the OPF and APF files, EUROCONTROL provides PTD files where PTD stands for Performance Table Data. The PTD files contain a detailed table of computed performance values for the climb and descent phases. Computed performance values are also given for the cruise phase for flight levels greater than or equal to 30 (3,000ft). The purpose of this file is to provide the user of the BADA mathematical model of aircraft performance with a greater number of computed parameters, especially intermediate parameters used to compute the final which may be used to validate an implementation of the BADA model (Nuic, 2009).

The results from mission trajectories simulated with APMI were therefore validated against PTD files for three aircraft, a long-range jet (A345, Airbus A340-500), a medium to short-range jet (B737, Boeing 737-700) and a turboprop (AT45, ATR 42-500). Consequently, each constituent block of the APMI was validated i.e., the atmosphere, speed, thrust, drag, fuel, energy share factor and rate of climb and descent blocks. In the PTD files, the fuel consumption in climb is independent of the aircraft mass, thus only one value is given. There are three different climb rates, however, corresponding to low, nominal and high mass conditions. The results from mission trajectories simulated with APMI were checked against the high mass climb conditions, meaning, the aircraft was allowed to take off with MTOW. The rate of descent and fuel consumption in descent in the PTD is calculated assuming nominal mass. Values for other mass conditions are not given. The results from a mission trajectory simulated with APMI was checked against the medium mass descent, meaning that the aircraft was allowed to descend with an end of cruise weight set to the medium aircraft weight specified in the PTD file. Thus the climb and the descent phases were validated separately. The validation of a representative selection of mission trajectories simulated with APMI against the PTD files was successful and no errors were discovered.

2.4. Calculation of emissions

A SAE International standard (SAEAerospace, 2009) was used for the calculation of the emissions and the method selected was the Boeing Fuel Flow Method 2 (BFFM2) (Martin et al., 1996; DuBois and Paynter, 2006) developed by The Boeing Company. The BFFM2 is considered to be of a mature development status, meaning that it is well-established and used extensively (SAEAerospace, 2009). The data requirements, computations and results are considered to be of middle tier complexity. The method requires aircraft performance data, reference emissions and fuel flows as input. Its key component is an empirical technique which allows for the adjustment for atmospheric effects and the relationship between fuel flow and emission indices (EIs). It allows a predicted fuel flow, either modelled or measured, to be assigned an EI. For a first description of the method see Martin et al. (1996), Appendix D of Baughcum et al. (1996) and page 11–15 of Baughcum et al. (1996). For a EUROCONTROL correction of the method see Jelinek et al. (2004) and for a further description see DuBois and Paynter (2006). The latest documented version of the method, AIR5715, was used (SAEAerospace, 2009) as it provides clarification on issues with fitting curves to the data which were previously not explained. It also contains a comprehensive description and clarification of further issues that a user of the method may encounter.

Aircraft emit primarily CO_2, CO, H_2O, HC (hydrocarbons), NO_x and SO_x. The level of these emissions is quantified by EIs that specify the mass of the species released per unit mass of the fuel burned. EIs are typically depicted as a function of an engine power setting and a fuel flow rate. The level of emissions of CO_2 and H_2O depends on the fraction of hydrogen and carbon contained in the fuel (Baughcum et al., 1996) and on the quantity of fuel consumed only. Similarly, the emissions of SO_x depend on the level of sulphur compounds in the fuel and arise from sulphur impurities in the fuel (Baughcum et al., 1994). Therefore, the CO_2, H_2O and SO_x EIs are constant. The values used in this project, taken from EUROCONTROL (Celikel and Jelinek, 2001), are summarised in Table 5.

The emissions of NO_x, CO and HC depend on the internal conditions of the engine. NO_x is produced primarily through reactions between oxygen and nitrogen in the high temperature regions of the engine combustor. Therefore NO_x emissions are sensitive to the combustor pressure and temperature, the fuel flow rate and the geometry of the combustor (Baughcum et al., 1996). Conditions favourable to NO_x production are attained at high thrust conditions during take-off. Conditions favourable to CO and HC production are attained at low engine power settings where the temperature is low and the com-

Table 5
$EICO_2$, EIH_2O and $EISO_x$ in grams of species per kilogram of fuel. The $EISO_x$ is given as gram equivalent SO_2 (Celikel and Jelinek, 2001).

Species	Emission Index (EI)
CO_2	3149 g/kg
H_2O	1230 g/kg
SO_x	0.84 g/kg

bustion less efficient i.e., incomplete combustion occurs. Therefore, NO_x, CO and HC EIs are engine specific and they vary from engine to engine.

Because a great deal of attention has always been given to air pollution levels in the vicinity of airports, EIs are limited to engine power settings common to the landing and the take-off (LTO) cycle, i.e., taxi in and out (idle mode), take-off, climb and approach. A linear approximation is used to derive emission indices at power settings and fuel flow rates between the reported values (Landau et al., 1994). Consequently, ICAO measures the NO_x emission index, $EINO_x$, the CO emission index, EICO, and the HC emission index, EIHC, at ISA standard sea level conditions at four engine power settings, namely 7%, 30%, 85% and 100% for engine certification purposes. The 7% power setting corresponds to an engine in idle mode, the 30% power setting corresponds to an engine in approach mode, the 85% power setting corresponds to an engine in climb out mode and the 100% power setting corresponds to an engine in take-off mode. Although hydrocarbon measurements of aircraft emissions by species have been made, only total HC emissions are considered in this work, with the EIHC given as gram equivalent methane (CH_4).

Boeing's empirical method allows for the calculation of emissions of NO_x, CO and HC given engine fuel flows and the EIs at the four power settings obtained from ICAO engine certification data. The method correlates the EIs at the four power settings and scales them for ambient temperature, pressure, humidity and Mach number. The method is summarised below.

First, fuel flows at the four power settings corresponding to take-off, climb out, approach and idle (referred to as reference fuel flows) measured at reference conditions (ISA, standard sea level conditions) are corrected to account for the installation effects of engine air bleed (Baughcum et al., 1996). Next, a log–log relationship is developed between the fuel flow and the EIs at reference conditions. The HC and CO fitted curves are bilinear (two slopes), while the NO_x is a point-to-point fit. These lines represent the trends of the EIs at different fuel flows. A modelled fuel flow is then converted from a fuel flow at flight conditions to a fuel flow at reference conditions. EIHC, EICO and $EINO_x$ are derived at reference conditions from the log–log curve fits and converted to EIHC, EICO and $EINO_x$ at flight conditions. As an EI specifies how many grams of the species in question are released per kilogram of fuel burned, it is then possible to calculate the amount of species released.

2.4.1. Assumptions and issues

A number of assumptions was made when calculating the aircraft emissions and a number of issues arose in this process. They are:

1. Relative humidity was assumed to be 60%.
2. The specific heat ratio was set to 1.4.
3. Engine deterioration effects were not modelled.
4. It was assumed that the log–log curve fit was of acceptable fidelity for all engines modelled.
5. EIs were extrapolated below the 7% engine power setting.
6. ICAO engine data used is engine specific, while the BADA fuel flow data is airframe specific. This led to a disconnect between the modelled (required) fuel flow and the ICAO reference (provided) fuel flow where the required fuel flow was greater than the provided.
7. The method is intended to be used with the ICAO Aircraft Engine Emission Databank for jets. Further tests will need to be conducted to better understand the method's applicability to turboprops (SAEAerospace, 2009). It was applied to the set of 23 turboprops modelled in this project.

With regard to point number 4 which is an assumption and the EIHC and EICO, the log–log curve fit was either standard or non-standard. A standard fit of the log–log curve was defined in AIR5715 (SAEAerospace, 2009) as one where a "slanting line" was fitted through the 7% and 30% data points, a "horizontal line" was fitted through the 85% and 100% data points, the two lines were extended until they intersected at a point between the 30% and the 85% data point. An example of a standard EIHC and EICO log–log curve fit is shown in Fig. 2. Fig. 2 also shows an example of the $EINO_x$ log–log curve fit which is always standard as it is a simple point-to-point fit. A non-standard log–log curve fit for the EIHC and/or the EICO was identified when a "slanting line" was fitted through the 7% and 30% data points, a "horizontal line" was fitted through the 85% and 100% data points, the two lines were extended and intersected either on the right hand side of the 100% data point as shown in Fig. 3 i.e., outside of the ICAO data range, or above the 30% data points as shown in Fig. 4. A non-standard situation was also defined if any of the data points (EIs) for the four engine power settings were equal to 0 in the ICAO databank.

A non-standard log–log curve fit for either the EIHC or the EICO cannot be used as there exists a disconnect between the fitted lines. A method was developed to account for the non-standard log-log curve fits and a solution was provided that allowed for the connection of the two badly fitted lines. The solution is shown in Figs. 5 and 6 and was applied to all the jet and turboprop engine data sets where a non-standard log–log curve fit was identified in the first instance.

Out of the 57 jet engine data sets used, 22 were completely standard while 35 exhibited a non-standard log–log curve fit and/or contained 0 data points. Out of the 23 turboprop engine data sets used, 3 were completely standard while 20 exhibited a non-standard log–log curve fit and/or contained 0 data points. Note that in some instances, an engine data set contained 0s and was exhibiting a non-standard log–log curve fit which raises the question of whether the 0s in the data give rise to the non-standard log–log curve fit. In all cases, the $EINO_x$ log–log curve fits were standard.

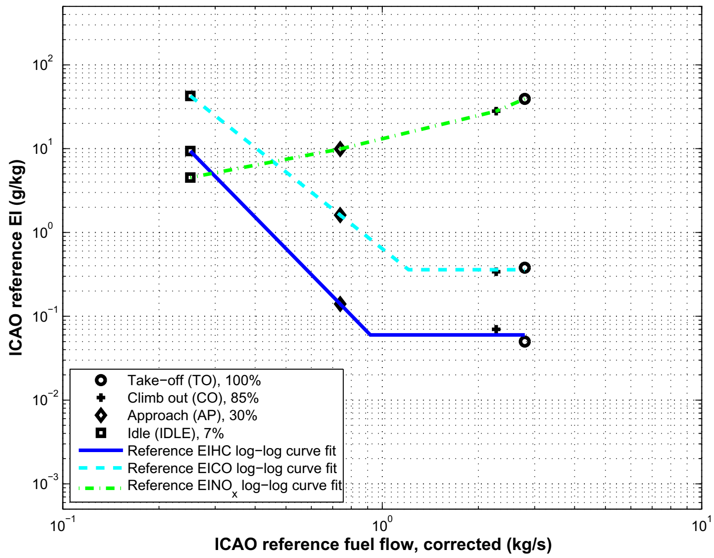

Fig. 2. The BFFM2 EIHC and EICO standard log–log curve fits and the EINO$_x$ log–log curve fit (always standard).

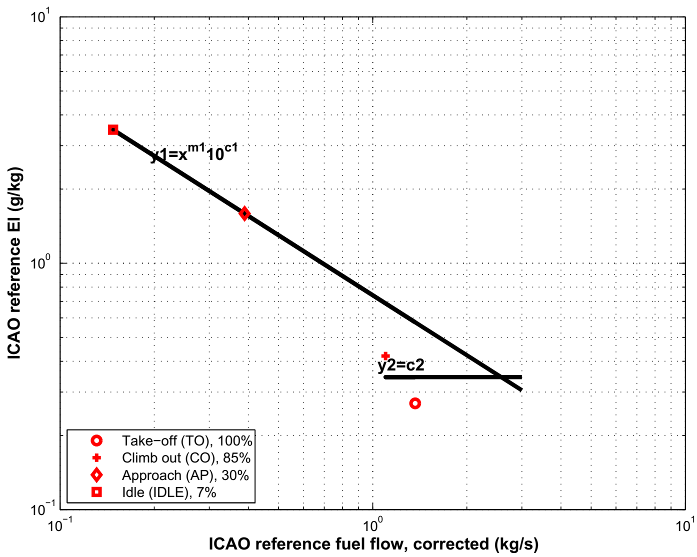

Fig. 3. The BFFM2 non-standard EIHC or EICO log–log curve fit where the two regression lines intersect beyond the ICAO reference fuel flow data range.

With regard to point number 5 which is an issue, a solution was implemented whereby two data sets were stored for each trajectory simulation. Letting the BADA fuel flow be the required fuel flow and the ICAO reference fuel flow the provided fuel flow, where a discrepancy existed (i.e., where the required fuel flow was greater than the provided fuel flow) one data set was calculated for the provided fuel flow and another for the required fuel flow. This allows for an estimate of the effect of the discrepancy on mission fuel burn and emissions to be calculated (a follow on activity). In the case where a discrepancy existed, the data set corresponding to the required fuel flow was used to calculate the emissions. Note that when the required fuel flow was greater than the provided fuel flow, the model was attempting to extrapolate the EIs beyond the ICAO data range i.e., beyond the 100% engine power setting.

With regard to assumption number 5, although the 7% engine power setting is the standard ICAO power setting used to represent idling and taxiing power, actual power usage can be less (SAEAerospace, 2009). While the changes to NO$_x$ may not be significant when modelling below the 7% power setting, the changes to EIHC and EICO can be significant (SAEAerospace, 2009). As a result, extrapolations below 7% power setting are recommended to properly model emissions, but care must be taken since erroneously high emissions could be generated for some engines (SAEAerospace, 2009).

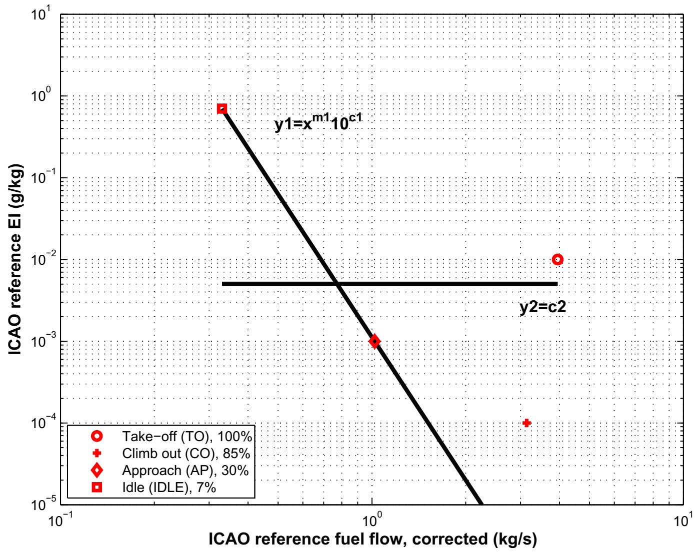

Fig. 4. The BFFM2 non-standard EIHC or EICO log–log curve fit where the two regression lines intersect above the ICAO reference approach (30%) fuel flow data point.

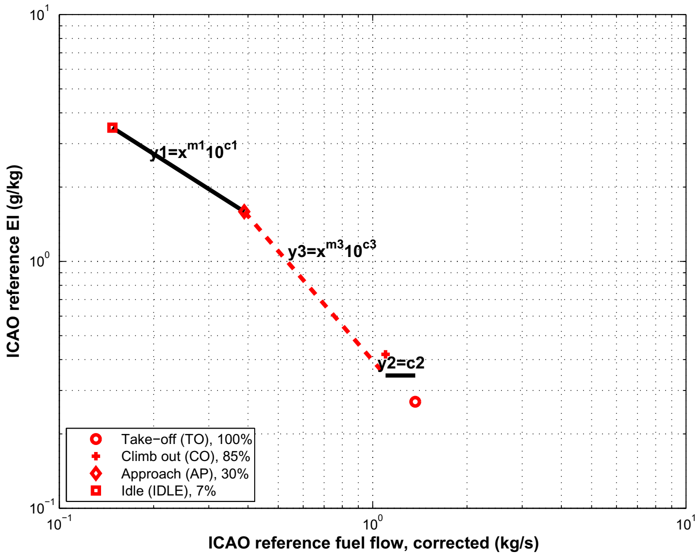

Fig. 5. The correction applied to the BFFM2 non-standard EIHC or EICO log–log curve fit where the two regression lines intersect beyond the ICAO reference fuel flow data range.

2.4.2. Validation

The BFFM2 has been validated by the ICAO Committee on Aviation Environmental Protection (CAEP), Working Group 3 (WG3). A ±10% accuracy for individual data points for HC, CO and NO_x was found. However, the HC and CO error was found to be greater at power settings below 7%. The International Panel on Climate Change (IPCC) 1999 Special Report Aviation and the Global Atmosphere validated cruise NO_x emissions and found them to be underestimated by 12% on average.

The derivation of the BFFM2 log–log curve fits was automated in MATLAB for all the 80 engines used. This was checked against the example in AIR5715 (SAEAerospace, 2009), using the jet engine Trent 892 with satisfactory outcome, meaning the automated derivation yielded $EIHC_{ref}$, $EICO_{ref}$ and $EINO_{x,ref}$ log–log curve fits fits equal to those given in the example.

The implementation of the BFFM2 within APMI was checked against the automated derivation i.e., fuel flows calculated with APMI were assigned reference EIs using the automated derivation and compared with those calculated within APMI with a satisfactory outcome.

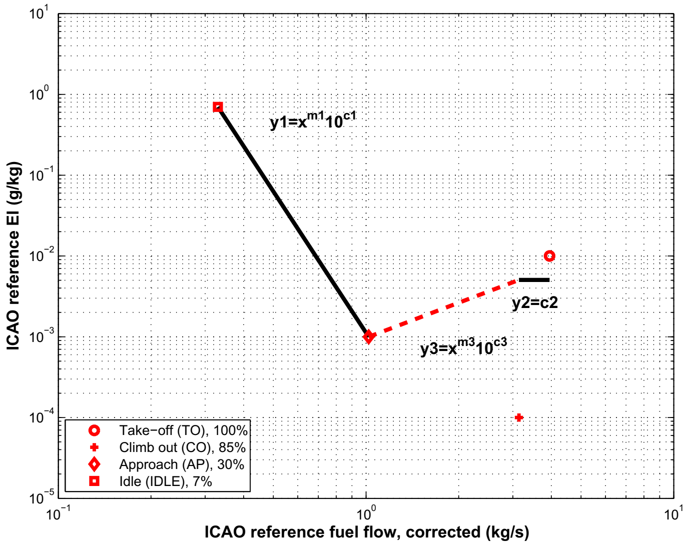

Fig. 6. The correction applied to the BFFM2 non-standard EIHC or EICO log–log curve fit where the two regression lines intersect above the ICAO reference approach (30%) fuel flow data point.

2.5. Modelling the global commercial fleet with APMI

APMI was designed to take three parameters as input: an ICAO aircraft code, a mission type designator (domestic/international, d/i) and a distance (km). For example, (B737, d, 509) would be a valid APMI input parameter triplet. Once specified, the input parameter triplets were fed to APMI and a simulation of the mission was run on University of Bristol's supercomputer BlueCrystal. During the mission simulation the whole mission trajectory of the aircraft used was sampled and assigned fuel use (mission fuel burn and reserve fuel) and emissions data.

All the input parameter triplets used (parameter combinations for short) were obtained as follows: every row in the database CAPSTATS was scanned and all three input parameters were extracted from each row. Each row in the database represents a record of the sum of all flights that took place during a particular month of a particular year, on a particular route, by a particular airline, using a particular aircraft. Duplicated and invalid parameter combinations were removed from this set and the remaining distinct, valid parameter combinations were grouped into sets according to the origin continent and the destination continent of the flight, as seen in Fig. 7. There were 131,942 distinct and valid parameter combinations in total and these accounted for all traffic between and within Africa (AF), Asia (AS), Central America (CA), the Caribbean (CB), Europe (EU), Middle East (ME), North America (NA), South America (SA) and Australasia (SW) between 2005 and 2011. A parameter combination was valid if all the constituent parameters were specified and non-zero, for example (B737,d,509). Instances of parameters where an IATA code had not been assigned an ICAO code, hence no OPF file, were deemed invalid, for example (,d,279). Instances where the distance was unspecified, for example (DH8C,d,) were also deemed invalid. It was always possible to assign a mission type to a parameter combination. As there was a large overlap between the sets corresponding to traffic between and within the 9 continents, the individual sets were pooled and all duplicates removed. The total number of unique, valid parameter combinations was 90,762. Each unique, valid parameter combination corresponds to one mission trajectory simulation with APMI. Hence in total 90,762 mission trajectory simulations were performed with APMI.

A minimum range and a maximum cruise range was defined for each aircraft. The minimum range was calculated as the distance covered in climb to 2,000 ft followed by an immediate descent in the first iteration, taking off with maximum takeoff weight. The altitude 2,000 ft was chosen because it is the lower threshold altitude for the phase cruise (CR) as defined in the BADA mathematical model of aircraft performance, meaning, the lowest altitude at which the aircraft could enter the cruise phase. If the distance parameter was less than the minimum range, the parameter combination was noted and omitted from the set. In total, the number of parameter combinations affected was 65 (0.07%).

A maximum cruise range for each aircraft was set to the distance taken from the EUROCONTROL Aircraft Performance Database (EUROCONTROL, 2013). There were instances of records of flights in CAPSTATS that appeared to be missions much longer than the aircraft maximum cruise range extracted from the EUROCONTROL Aircraft Performance Database. This issue was queried with the data provider (RDC Aviation via Flightglobal). RDC Aviation conceded that there were records of routes in the database that did exceed RDC Aviation's own range data. RDC Aviation's range data was built up over the past ten years by RDC Aviation from researching manufacturer data. It was concluded that the number of routes affected was small (61 flights out of 72,987 in November 2011) and no further explanation was given. It was hypothesised that where the distance flown appeared outside of the maximum range, the flights may have been reported as direct to the data provider, but that the aircraft may have landed somewhere for refuelling. This could also be due to misleading airport codes having been supplied

	AF	AS	CA	CB	EU	ME	NA	SA	SW
AF	4,908	256	0	2	4,048	1,033	53	29	14
AS	248	20,283	1	17	3,356	1,827	361	8	437
CA	0	1	265	29	17	0	392	71	3
CB	2	17	32	993	409	0	1,747	266	0
EU	4,156	3,373	17	426	31,507	2,105	1,619	340	6
ME	1,014	1,839	0	0	2,134	2,446	85	11	21
NA	55	349	446	1,841	1,644	80	25,448	460	60
SA	30	7	64	271	340	10	434	5040	8
SW	16	433	3	0	7	20	59	5	2,588

Intracontinental, AS, EU, NA

Intracontinental, other

Intercontinental, AS, EU, NA to AS, EU, NA

Intercontinental, AS, EU, NA to other

Intercontinental, other to AS, EU, NA

Intercontinental, other to other

Fig. 7. The number of distinct and valid APMI input parameters by origin and destination continent. Intracontinental refers to all flights within the same continent, while intercontinental refers to all flights between two different continents.

to the data collector, as in the case of the database used for the AERONOX inventory (European Commission, 1997). It was noted with the AERONOX inventory that sometimes a locally devised airport code had been supplied which was the same as an existing IATA airport code for an airport in a different location. This led to an aircraft mission where a small aircraft would fly nonstop from Glasgow to Singapore. It was not possible to obtain the range data from RDC Aviation, nor was it possible to obtain a suitable, comprehensive and free source of aircraft cruise ranges (Jane's All the World's Aircraft online edition would have been a suitable source, but not gratis).

APMI was also run with all the parameter combinations where the mission distance parameter was greater than the maximum cruise range. If the simulation was successful, the simulated cruise distance was checked against the maximum cruise distance and if in excess, the result of the simulation was discarded. In total, the number of parameter combinations affected was 1658 (1.83%). 88 (0.10%) simulations where the mission distance parameter was greater than the maximum cruise range failed, meaning APMI failed to simulate the mission trajectory. In these cases, it could not be decided whether the simulated cruise distance was within the maximum range. These simulations were discarded.

In total 98% (88,951) of the total number of unique, valid parameter combinations were successfully run with APMI. Hence 6,622,219 out of the 6,694,449 flights (98.9%) in the database were successfully assigned a mission fuel burn and emissions of CO_2, CO, H_2O, HC, NO_x and SO_x as well as a reserve fuel requirement. The results for each mission trajectory simulation were stored in an ASCII text file. The output files were parsed and additional relations were added to the database for each row that contained a valid input parameter combination. In this way, every flight record in CAPSTATS was assigned a mission fuel burn, a reserve fuel requirement, a mission distance, a mission time, a mission cruise altitude and emissions of CO_2, CO, H_2O, HC, NO_x and SO_x. Where a row could not be assigned fuel burn and emissions data, the reason was noted. The possible reasons for this were: invalid parameter(s), distance < minimum range, CR distance > CR maximum range, or APMI failure.

3. Discussion

As there is no overlap in year between the estimates from SAGE in the original technical documentation (Kim et al., 2005) nor in Kim et al. (2007) where the results were summarised, the figures from Wilkerson et al. (2010) were used to compare the two models. Wilkerson et al. (2010) published an estimate for 2006 obtained from AEDT into which SAGE was incorporated. The results of the comparison are summarised in Table 6 which gives the percent differences in the estimates of the number of departures, mission fuel burn and CO_2, CO, H_2O, HC, NO_x and SO_x emissions for the year 2006 calculated using APMI and the estimates from Wilkerson et al. (2010) calculated using SAGE.

Table 6 shows that the total global number of departures modelled with the APMI software on which the estimates of the emissions of CO_2, CO, H_2O, HC, NO_x and SO_x are based is $\approx 8\%$ lower.

The two models use very similar air traffic movements data sources (SAGE uses OAG and APMI uses CAPSTATS), therefore it is unlikely that a large portion of the difference is due to the air traffic movements data sources. Recall that there was a 94% overlap in the routes on which information was reported in the two databases and in 38% of those cases the databases also reported exactly the same number of departures. In the remaining 62% of the cases the number of the departures reported in CAPSTATS was either higher or lower. However, SAGE complemented the OAG flight schedules data with radar data capturing cargo, military, charter and unscheduled flights (Kim et al., 2005). This is where the greatest part of this difference likely comes from. In effect, the $\approx 8\%$ difference in the number of global departures modelled by APMI can be thought of as an estimate of the number of unscheduled departures not captured by CAPSTATS. This serves as a further validation of the CAPSTATS air traffic movements database.

Consequently, and also due to the fact that in APMI flight trajectories were optimised for least fuel burn, the mission fuel burn estimate given by APMI is approximately 20% lower compared to that given by SAGE in Wilkerson et al. (2010). It is uncertain what fraction of the 20% underestimate is due to APMI modelling a different number of commercial departures, APMI excluding unscheduled departures and to the fuel burn optimisation. As the emissions of CO_2 and H_2O depend on mission fuel burn, these are also $\approx 20\%$ lower. Note that higher EIs for CO_2 and H_2O were used in SAGE (+6 g/kg for $EICO_2$ (3155 g/kg) and +7 g/kg for EIH_2O (1237 g/kg)). It is also unclear whether the $EICO_2$ and/or the EIH_2O changed between the first publication of SAGE and its subsequent inclusion in the AEDT.

Emissions of SO_x depend on mission fuel burn and the sulphur content of the fuel. The SO_x emissions estimate calculated with APMI is $\approx 40\%$ lower than that given by Wilkerson et al. (2010). The lower number of departures modelled in APMI, the exclusion of unscheduled departures and the optimisation of flight trajectories for least fuel burn will account for some of this difference. However, a slightly higher $EISO_x$ was used in APMI compared to SAGE (0.84 g/kg in APMI versus 0.8 g/kg in SAGE). Hence, there is a portion of the difference in the SO_x estimate that cannot be explained by the different modelling conditions in APMI and SAGE. It is speculated that the 40% difference in the SO_x estimate is mainly a consequence of the unknown fuel sulphur content.

The estimates of the emissions of CO, HC and NO_x calculated with APMI are higher than those calculated with SAGE, $\approx 10\%, \approx 140\%$ and $\approx 30\%$ respectively. As the emissions of HC, CO and NO_x do not depend on the mission fuel burn alone, hence not solely on the number of departures modelled, there are a number of explanations for these differences.

They are: the number of generic aircraft types used in APMI and SAGE, the number of different engines modelled, the assumed airframe to engine match, the use of ICAO prescribed taxi in and taxi out times in APMI (not in SAGE), the use of different data sources for turboprop engine fuel flows and EIs in APMI, modelling a large number of jet engines which exhibit a non-standard behaviour with respect to EICO and EIHC, errors associated with modelling EICO and EIHC below the 7% engine power setting (in idle mode i.e., during taxi out and taxi in) and assumptions made about the thrust setting in the take-off and climb out phase of a typical aircraft mission. These explanations are elaborated upon below.

It is stated in Kim et al. (2005) that "even though substitution aircraft data are necessarily used for some aircraft types, the intention with SAGE is to preserve as much of the specificity of each flight as possible. Therefore, compromises associated with using generic aircraft types and engines are not made". It is however unclear how many of the 200 different aircraft types considered by SAGE were modelled with 'substitution aircraft'. A scan of Appendix D of Kim et al. (2005) shows that what are generally understood to be generic aircraft types were used as for example six different OAG aircraft codes were mapped to the BADA code A306 (A303, A304, A305, A306, A308 and A309). It is unclear how many such reductions were made in SAGE.

In SAGE, the world fleet registration database from BACK Aviation was used for the airframe to engine match. BACK contains a listing of worldwide commercial aircraft built since 1940 (Kim et al., 2005). Each aircraft listing contains an engine model specification which is more accurate than the airframe to engine match used within this work. However, a scan of

Table 6
Comparison with estimates for 2006 from (Wilkerson et al., 2010).

Source	Departures (10^6)	Fuel burn (Tg)	CO_2 (Tg)	CO (Tg)	H_2O (Tg)	HC (Tg)	NO_x (Tg)	SO_x (Tg)
(Wasiuk, 2014)	28.9	152.2	479.3	0.742	187.2	0.238	3.517	0.128
(Wilkerson et al., 2010)	31.3	188.2	594.3	0.679	232.8	0.098	2.7	0.222
%Δ	−7.7	−19.1	−19.4	9.3	−19.6	142.9	30.3	−42.3

Appendix E of Kim et al. (2005) shows that approximately 82 distinct engines were modelled in SAGE, compared to 78 in APMI.

Due to a lack of detailed taxi in and taxi out times, ICAO prescribed taxi in and taxi out times were used in APMI which are fixed at 19 and 7 min respectively for both jets and turboprops. SAGE modelled ground operations more closely using airline on-time performance data from the Bureau of Transportation Statistics (Kim et al., 2005). Results from APMI showed that approximately one third of the total global mission time was spent on the ground (taxiing out and in) on average between 2005 and 2011 when using the ICAO prescribed taxi in and taxi out times. This will have a significant impact on the CO and HC emissions as these are the two mission phases favoured by high CO and HC EIs. Accordingly, APMI showed that over 40% of the total global aircraft CO and HC emissions were released on the ground and below 1 km on average between 2005 and 2011 (Wasiuk, 2014). Therefore, when modelling aircraft emissions the time spent on the ground will have a direct and important impact on the global totals of HC and CO.

SAGE used FAA's Emissions and Dispersing Modelling System (EDMS) for the turboprop engine data, while the Swedish Defense Research Agency (FOI) Turboprop Engine Emissions Database (Hasselrot, 2002) was used in APMI. FOI states that in the Turboprop Engine Emissions Database data are presented in the same format as in the ICAO Engine Emissions Database for jet engines, but have not been endorsed by ICAO in a certification process. FOI further states that it should be noted that these data have many inaccuracies resulting primarily from the unregulated test methodologies. However, the data are considered to be the best available and may be used for emissions inventories (Hasselrot, 2002). Results from APMI showed that between 90% and 100% of the total global CO, HC and NO_x emissions were due to jet engines, hence the differences in the estimates of these between the two models due to the use of differing sources of turboprop engine data are likely to be small.

It was pointed out in AIR5715 (SAEAerospace, 2009) that the errors associated with the calculations of CO and HC emissions, in particular in idle mode (between the 7% and 30% engine power setting) were between 10% and 15% but could be significantly greater below the 7% engine power setting. In SAGE, a cap was implemented whereby CO and HC emissions were not modelled at fuel flows below the 7% engine power setting (Kim and Rachami, 2008) due to the large modelling uncertainties associated with EIHC and EICO below the 7% engine power setting. This is where the largest proportion of the differences in the CO and HC global totals given by APMI and SAGE likely comes from. Effectively, the differences serve as a first quantification of the magnitude of the large modelling uncertainties associated with EIHC and EICO below the 7% engine power setting. They show that the EIHC is affected by these modelling uncertainties to a larger extent than the EICO.

Note that in APMI EIs were extrapolated below the 7% engine power setting but were not extrapolated above the 100% engine power setting. The rationale for this is: when APMI asks for emissions to be assigned to a fuel flow that has been estimated with the BADA model and this fuel flow is below the 7% engine power setting, this is technically feasible. This means that the engine is able to generate a fuel flow below that at the 7% engine power setting (down to a 0% engine power setting). However, it is technically impossible that the engine provide a fuel flow above its capacity, i.e., above its 100% power setting if we consider the 100% power setting to be its maximum capacity.

Due to a lack of guidance on how to deal with the non-standard log–log curve fits that the EIHC and EICO were affected by in some instances, FAA developed own solutions. This is because the BFFM2 documentation available until 2009 did not clarify how to correct the BFFM2 EICO and/or EIHC fit in those cases and SAGE was created before 2009. The solutions deployed in SAGE (page 45 of Kim et al. (2005)) differ from those prescribed in AIR5715 (SAEAerospace, 2009) which were used in APMI. This will therefore contribute to the difference in the HC and CO estimates.

With respect to $EINO_x$, all engines modelled in APMI exhibited a standard behaviour hence errors due to non-standard behaviour with respect to $EINO_x$ can be ruled out. Here, the mapping of engines to airframes will have an impact on the overall estimate. Also, it is possible that the fuel burn optimisation may have incurred a penalty in terms of NO_x as the altitude where least fuel is burned may not correspond to the altitude at which the running of the engine incurs the lowest $EINO_x$. Simulations with a modified version of APMI optimising for least NO_x will be able to ascertain if this is the case. Also, it would appear that a log–log regressed linear fit was used for the $EINO_x$ in SAGE whereas the 2009 SAEAerospace standard uses a point-to-point fit which was adapted in APMI.

Furthermore, reduced thrust take-off can have a significant effect on fuel burn and emissions predictions, for example NO_x (SAEAerospace, 2009). In APMI, a reduced climb power in climb out from 35 ft to the missions cruise altitude was used. The reduced climb power was introduced into the BADA model of aircraft performance to allow for simulation of climbs using less than the maximum climb setting. In day to day operations, many aircraft use a reduced setting during climb in order to extend engine life and save costs. The correction factors that are used to calculate the reduction in power were obtained in an empirical way and have been validated with the help of air traffic controllers. In BADA, climbs that are performed using the full climb power will result in profiles that match the reference data that is found in the flight manual of the aircraft. Climbs with reduced power will give a realistic profile (Nuic, 2009). In SAGE, maximum power is assumed for the take-off mode and up to 2000 ft at which point, reduced power is modelled (Kim et al., 2005).

4. Conclusions

In this paper, the design and execution of the Aircraft Performance Model Implementation (APMI) software for the calculation of global commercial aviation fuel burn and emissions was described, as were the individual software components and the overall implementation process. Collectively this includes research of a commercial air traffic movements data source, procurement and preparation of the air traffic data, conversion of the data from an online source to a portable database, normalisation of the database, a mathematical model of aircraft performance for all phases of a flight, a procedure for the calculation of aircraft emissions, a mission fuel burn algorithm, domestic and international reserve fuel requirement calculation, a cruise altitude allocation method, a cruise distance calculation, all the underlying assumptions made and any issues that arose in the process.

Results from the APMI software were compared with results from FAA's SAGE for the year 2006. The comparison showed that the global volume of commercial air traffic (measured by the number of departures) modelled by APMI was 8% lower. APMI used an alternative to the OAG commercial air traffic statistics data source employed in SAGE called CAPSTATS. It was shown that the OAG and CAPSTATS air traffic movements data sources are very similar hence it is unlikely that a large portion of the 8% difference is due to SAGE incorporating OAG data. SAGE complemented the OAG flight schedules with radar data. The greatest part of the 8% difference is likely due to the inclusion of radar data capturing cargo, military, charter and unscheduled flights. The 8% difference can effectively be thought of as an estimate of the number of unscheduled departures not captured by CAPSTATS.

The comparison further showed that the mission fuel burn and consequently the CO_2 and H_2O estimates from APMI were $\approx 20\%$ lower than those predicted by SAGE for 2006. This difference is explained by APMI modelling a different number of commercial departures and excluding unscheduled departures, using lower EIs for CO_2 and H_2O and to the fuel burn optimisation employed in APMI.

The estimate of the total global aircraft SO_x emissions was $\approx 40\%$ lower than that predicted by SAGE. This difference has the same cause as that for CO_2 and H_2O. However, a slightly higher $EISO_x$ was used in APMI compared to SAGE therefore there is a portion of the difference in the SO_x estimate that cannot be explained by the different modelling conditions in APMI and SAGE.

The estimates of the CO, HC and NO_x emissions were 10%, 140% and 30% higher than those predicted by SAGE respectively. The differences between the CO and HC estimates serve as a first quantification of the magnitude of the large modelling uncertainties associated with the EIHC and EICO below the 7% engine power setting, HC in particular, when the BFFM2 is applied to the calculation of HC and CO emissions. In SAGE, a cap was implemented whereby the EIHC and EICO were not modelled at fuel flows below the 7% engine power setting; a cap was not applied in APMI however. Also, these differences highlight the importance of the log–log curve fits used with the BFFM2.

The execution of the APMI software was performed on the University of Bristol's High Performance Computing (HPC) cluster BlueCrystal demonstrating a novel approach to modelling aircraft fuel burn and emissions and the computational advantages that High Performance Computing can offer this area of research. Previously, modelling aircraft fuel burn and emissions may have been restricted to estimates for one or a handful of years only due to computational intensity. High Performance Computing offers a vast improvement in that respect.

Ultimately, this paper demonstrates that obtaining a consistent and extended timeline of estimates of commercial air traffic fuel burn and emissions is fundamentally limited by the lack of a free, publicly available and suitable air traffic movements database. It shows that, when such a database can be procured, this can be achieved in a relatively short time by a small team of researchers as opposed to large organisations like NASA, the FAA or the EC.

Acknowledgements

We thank Stephen Roome (University of Bristol, Advanced Computing Research Centre), Callum Wright (University of Bristol, Advanced Computing Research Centre), Tom Gidden (http://www.linkedin.com/in/tomgidden), Dr. Matt Oates (University of Bristol), Sergio Angel Araujo Estrada (University of Bristol, Department of Aerospace Engineering) Andy Williams and Chris Hume. We also thank the Engineering and Physical Sciences Research Council (EPSRC) (Grant EP/5011214) and the Natural Environment Research Council (NERC) (Grants NE/J009008/1 and NE/I014381/1), University of Bristol Faculty of Engineering and School of Chemistry for funding various aspects of this work.

References

Bauer, E., 1979. A catalog of perturbing influences on stratospheric ozone, 1955–1975. J. Geophys. Res. 84 (C11), 6929–6940.
Baughcum, S.L., Henderson, S.C., Hertel, P.S., Maggiora, D.R., Oncina, C.A., 1994. Stratospheric emissions effects database development. NASA-CR-4592, Boeing Commercial Airplane Group, National Aeronautics and Space Administration.
Baughcum, S.L., Tritz, T.G., Henderson, S.C., Pickett, D.C., 1996. Scheduled civil aircraft emission inventories for 1992: database development and analysis. NASA-CR-4700, National Aeronautics and Space Administration.
Boeing 737-700 Technical Characteristics. <http://www.boeing.com/boeing/commercial/737family/pf/pf_700tech.page> (accessed 30.05.14).
Boeing 737-800 Technical Characteristics. <http://www.boeing.com/boeing/commercial/737family/pf/pf_800tech.page> (accessed 30.05.14).
CAPA Centre for Aviation. <http://www.centreforaviation.com/about-capa/glossary/> (accessed 13.03.12).
Celikel, A., Jelinek, F., 2001. Forecasting civil aviation fuel burn and emissions in Europe. EUROCONTROL Experimental Centre.
DuBois, D., Paynter, G.C., 2006. Fuel Flow Method 2 for Estimating Aircraft Emissions. SAEInternational, The Boeing Company.
EUROCONTROL Aircraft Performance Database. <http://contentzone.eurocontrol.int/aircraftperformance/> (accessed 10.12.13).
EUROCONTROL Base of Aircraft Data (BADA). <http://www.eurocontrol.int/services/bada> (accessed 29.01.14).
Eyers, C.J., Norman, P., Middel, J., Plohr, M., Michot, S., Atkinson, K., 2004. AERO2k global aviation emissions inventories for 2002 and 2025. European Commission, QinetiQ Ltd.
Filippone, A., 2006. Flight Performance of Fixed and Rotary Wing Aircraft. Butterworth-Heinemann.

Gardner, R.M., Adams, K., Cook, T., Deidewig, F., Ernedal, S., Falk, R., Fleuti, E., Herms, E., Johnson, C.E., Lecht, M., Lee, D.S., Leech, M., Lister, D., Massé, B., Metcalfe, M., Newton, P., Schmitt, A., Vandenbergh, C., Van Drimmelen, R., 1997. The ANCAT/EC global inventory of NO_x emissions from aircraft. Atmos. Environ. 31 (12), 1751–1766.

Gilmore, C.K., Barrett, S.R.H., Koo, J., Wang, Q., 2013. Temporal and spatial variability in the aviation NO_x-related O_3 impact. Environ. Res. Lett. 8 (3).

Greenwell, D., 2006/2007. Cruise Performance. Course Material, Aeronautics & Mechanics AENG11301, Department of Aerospace Engineering, University of Bristol, Bristol, UK, 14 p.

Hasselrot, A., 2002. Confidential Database for Turboprop Engine Emissions. Swedish Defence Research Agency.

Hidalgo, H., Crutzen, P.J., 1977. The tropospheric and stratospheric composition perturbed by NO_x emissions of high-altitude aircraft. J. Geophys. Res. 82 (37), 5833–5866.

ICAO Airport Air Quality Manual, first ed., 2011. International Civil Aviation Organisation.

ICAO Aircraft Engine Emissions Databank, 18th ed., 2012. International Civil Aviation Organization Committee on Aviation Environmental Protection.

ICAO, Global trends in air transport: traffic, market access & challenges. Professor Senguttuvan, P.S., <http://www.icao.int/Meetings/wrdss2011/Documents/DevelopmentForum2008/Senguttavan.pdf> (accessed 27.02.14).

ICAO Glossary. <http://d1fmezig7cekam.cloudfront.net/VPP/Global/Flight/ICAO/GLOSSARY.pdf> (accessed 27.02.14).

Innovata. <http://www.innovata-llc.com/about-innovata/about-innovata.html> (accessed 13.03.12).

IPCC Working Groups I and III, Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer, 1999. Aviation and the global atmosphere. In: Penner, J.E., Lister, D.H., Griggs, D.J., Dokken, D.J., McFarland, M. (Eds.). Cambridge University Press.

Jelinek, F., Carlier, S., Smith, J., 2004. The Advanced Emission Model (AEMIII) Version 1.5, Appendices A, B and C to the Validation Report EEC/SEE/2004/004. EUROCONTROL Experimental Centre.

Kim, B., Rachami, J., 2008. Aircraft emissions modeling under low power conditions. Technical Report, Observatory for sustainability in aviation. <http://www.obsa.org/Lists/Documentacion/Attachments/84/Aircraft_Emissions_Modeling_Low_Power_EN.pdf>.

Kim, B., Fleming, G., Balasubramanian, S., Malwitz, A., Lee, J., Ruggiero, J., Waitz, I., Klima, K., Stouffer, V., Lond, D., Kostiuk, P., Locke, M., Holsclaw, C., Morales, A., McQueen, E., Gillette, W., 2005. System for assessing Aviations Global Emissions (SAGE), Version 1.5, Technical Manual. U.S. Department of Transportation, Massachusetts Institute of Technology, Federal Aviation Administration.

Kim, B.Y., Fleming, G.G., Lee, J.J., Waitz, I.A., Clarke, J.P., Balasubramanian, S., Malwitz, A., Klima, K., Locke, M., Holsclaw, C.A., Maurice, L.Q., Gupta, M.L., 2007. System for assessing Aviations Global Emissions (SAGE), Part 1: Model description and inventory results. Transport. Res. D – Tr. E. 12 (5), 325–346.

Landau, Z.H., Metwally, M., Van Alstyne, R., Ward, C.A., 1994. Jet aircraft engine exhaust emissions database development-year 1990 and 2015 scenarios. McDonnell Douglas Aerospace, National Aeronautics and Space Administration.

Lee, D.S., Pitari, G., Grewe, V., Gierens, K., Penner, J.E., Petzold, A., Sausen, R., 2010. Transport impacts on atmosphere and climate: aviation. Atmos. Environ. 44 (37), 4678–4734.

Little, A.D., 1975. Preliminary economic impact assessment of possible regulatory action to control atmospheric emissions of selected halocarbons. Prepared by Arthur D. Little, Inc. for Environmental Protection Agency, Office of Air Quality Planning and Standards.

Martin, R.L., Oncina, C.A., Zabeen, J.P., 1996. A Simplified Method for Estimating Aircraft Engine Emissions. The Boeing Company. Appendix C of Baughcum et al., 1996, Scheduled civil aircraft emission inventories for 1992: database development and analysis.

Nuic, A., 2009. User Manual for the Base of Aircraft DAta (BADA) Revision 3.7. EUROCONTROL Experimental Centre.

Nuic, A., 2011. User Manual for the Base of Aircraft DAta (BADA) Revision 3.9. EUROCONTROL Experimental Centre.

Olsen, S.C., Brasseur, G.P., Wuebbles, D.J., Barrett, S.R.H., Dang, H., Eastham, S.D., Jacobson, M.Z., Khodayari, A., Selkirk, H., Sokolov, A., Unger, N., 2013. Comparison of model estimates of the effects of aviation emissions on atmospheric ozone and methane. Geophys. Res. Lett. 40 (22), 6004–6009.

SAEAerospace, 2009. Procedure for the calculation of aircraft emissions, AIR5715. SAEInternational.

Schmitt, A., Brunner, B., 1997. Emissions from aviation and their development over time. Deutsche Zentrum für Luft- und Raumfahrt.

Suchkov, A., Swierstra, S., Nuic, A., 2003. Aircraft performance modelling for air traffic management application. In: 5th USA/Europe Air Traffic Management Research and Development Seminar, 23–27 June, Budapest, Hungary.

Sutkus, D.J., Baughcum, S.L., DuBois, D., 2001. Scheduled civil aircraft emission inventories for 1999: database development and analysis. Boeing Commercial Airplane Group, National Aeronautics and Space Administration.

The Airline Codes Website. <http://www.airlinecodes.co.uk/home.asp> (accessed 13.04.11).

The impact of NO_x emissions from aircraft upon the atmosphere at flight altitudes 8–15 km (AERONOX). Schumann, U. (Ed.), 1997. European Commission, Deutsche Zentrum für Luft- und Raumfahrt.

Wasiuk, D.K., 2014. Modelling aircraft emissions and their impact on atmospheric composition and ozone. Ph.D. thesis, Faculty of Engineering, Department of Aerospace Engineering, University of Bristol, Bristol, UK. Available from the University of Bristol Queens Building Library as an Inter Library Loan.

Wilkerson, J.T., Jacobson, M.Z., Malwitz, A., Balasubramanian, S., Wayson, R., Fleming, G., Naiman, A.D., Lele, S.K., 2010. Analysis of emission data from global commercial aviation: 2004 and 2006. Atmos. Chem. Phys. 10 (13), 6391–6408.